

**Chapter 2**  
**COASTAL CLASSIFICATION AND MORPHOLOGY**

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## Chapter IV-2 Coastal Classification and Morphology

### IV-2-1. Introduction

*a.* Since ancient times, men have gone to sea in a variety of vessels to obtain food and to transport cargo and passengers to distant ports. To navigate safely, sailors needed an intimate knowledge of the appearance of the coast from place to place. By the time that systematic study of coastal geology and geomorphology began, there already existed a large body of observational knowledge about seacoasts in many parts of the world and a well-developed nomenclature to portray coastal landforms. Geologists in the 19th and 20th centuries described coastal landforms, examined their origin and development as a function of geologic character, history, and dynamic processes, and devised classification schemes to organize and refine their observations.

*b.* The first part of this chapter discusses the coastal classification of Francis Shepard (1973). The second part describes specific coastal environments found around the United States following Shepard's outline.

### IV-2-2. Coastal Classification

*a. Introduction.* By its very nature, the coast is an incredibly complex and diverse environment, one that may defy organization into neat compartments. Nevertheless, the quest for understanding how shorelines formed and how human activities affect these processes has demanded that classification schemes be devised. Most have grouped coastal areas into classes that have similar features because of having developed in similar geological and environmental settings.

*b. Early classifications.* Many early geologists took a genetic approach to classification and distinguished whether the coast had been primarily affected by rising sea level (submergence), falling sea level (emergence), or both (compound coasts) (Dana 1849; Davis 1896a; Gulliver 1899; Johnson 1919; Suess 1888).

*c. Later classifications.* The best known of the modern classifications are those of Cotton (1952), Inman and Nordstrom (1971), Shepard (1937), with revisions in 1948, 1971 (with Harold Wanless), 1973, and 1976, and Valentin (1952). Except for Inman and Nordstrom (1971), these classifications emphasized onshore and shoreline morphology but did not include conditions of the offshore bottom. This may be a major omission because the submarine shoreface and the shelf are part of the coastal zone. Surprisingly few attempts have been made to classify the continental shelf. Shepard (1948; 1977) and King (1972) discussed continental shelf types, but their classifications are not detailed and contain only a few broadly defined types.

*d. Coastal classification of Francis Shepard.* Possibly the most widely used coastal classification scheme is the one introduced by Shepard in 1937 and modified in later years. It divides the world's coasts into primary coasts - formed mostly by non-marine agents - and secondary coasts - shaped primarily by marine processes. Further subdivisions occur according to which specific agent, terrestrial or marine, had the greatest influence on coastal development. The advantage of Shepard's classification is that it is more detailed than others, allowing most of the world's coasts to be incorporated. Although gradational shore types exist, which are difficult to classify, most coasts show only one dominant influence as the cause of their major characteristics (Shepard 1973). Because of its overall usefulness, Shepard's 1973 classification is reproduced in Table IV-2-1. Specific coasts are discussed in detail in this chapter, approximately following the outline of Shepard's table.

Table IV-2-1  
Classification of Coasts (Continued)

Excerpt from SUBMARINE GEOLOGY, 3rd ed. by Francis P. Shepard. Copyright 1948, 1963, 1973 by Francis P. Shepard. Reprinted by permission of Harper Collins Publishers.	Paragraph No.
<p>I. <i>Primary coasts</i> Configuration due to nonmarine processes.</p> <p>A. <i>Land erosion coasts</i> Shaped by subaerial erosion and partly drowned by postglacial rise of sea level (with or without crustal sinking) or inundated by melting of an ice mass from a coastal valley.</p> <ol style="list-style-type: none"> <li>1. <i>Ria coasts (drowned river valleys)</i> Usually recognized by the relatively shallow water of the estuaries which indent the land. Commonly have V-shaped cross section and a deepening of the axis seaward except where a barrier has built across the estuary mouth.</li> <li>2. <i>Dendritic</i> Pattern resembling an oak leaf due to river erosion in horizontal beds or homogeneous material.</li> <li>3. <i>Trellis</i> Due to river erosion in inclined beds of unequal hardness. <ol style="list-style-type: none"> <li>(a) <i>Drowned glacial erosion coasts</i> Recognized by being deeply indented with many islands. Charts show deep water (commonly more than 100 m) with a U-shaped cross section of the bays and with much greater depth in the inner bays than near the entrance. Hanging valleys and sides usually parallel and relatively straight, in contrast to the sinuous rias. Almost all glaciated coasts have bays with these characteristics.</li> <li>(b) <i>Fjord coasts</i> Comparatively narrow inlets cutting through mountainous coasts.</li> <li>(c) <i>Glacial troughs</i> Broad indentations, like Cabot Strait and the Gulf of St. Lawrence or the Strait of Juan de Fuca.</li> </ol> </li> <li>4. <i>Drowned karst topography</i> Embayments with oval-shaped depressions indicative of drowned sinkholes. This uncommon type occurs locally, as along the west side of Florida north of Tarpon Springs, the east side of the Adriatic, and along the Asturias coast of North Spain.</li> </ol> <p>B. <i>Subaerial deposition coasts</i></p> <ol style="list-style-type: none"> <li>1. <i>River deposition coasts</i> Largely due to deposition by rivers extending the shoreline since the slowing of the postglacial sea level rise.</li> <li>2. <i>Deltaic coasts</i> <ol style="list-style-type: none"> <li>(a) <i>Digitate (birdfoot)</i>, the lower Mississippi Delta.</li> <li>(b) <i>Lobate</i>, western Mississippi Delta, Rhone Delta.</li> <li>(c) <i>Arcuate</i>, Nile Delta.</li> <li>(d) <i>Cuspate</i>, Tiber Delta.</li> <li>(e) <i>Partly drowned deltas</i> with remnant natural levees forming islands.</li> </ol> </li> <li>3. <i>Compound delta coasts</i> Where a series of deltas have built forward a large segment of the coast, for example, the North Slope of Alaska extending east of Point Barrow to the Mackenzie.</li> <li>4. <i>Compound alluvial fan coasts straightened by wave erosion</i>.</li> <li>5. <i>Glacial deposition coasts</i> <ol style="list-style-type: none"> <li>(a) <i>Partially submerged moraines</i> Usually difficult to recognize without a field study to indicate the glacial origin of the sediments constituting the coastal area. Usually modified by marine erosion and deposition as, for example, Long Island.</li> <li>(b) <i>Partially submerged drumlins</i> Recognized on topographic maps by the elliptical contours on land and islands with oval shorelines, for example, Boston Harbor and West Ireland (Guilcher 1965).</li> <li>(c) <i>Partially submerged drift features</i></li> </ol> </li> <li>6. <i>Wind deposition coasts</i> It is usually difficult to ascertain if a coast has actually been built forward by wind deposition, but many coasts consist of dunes with only a narrow bordering sand beach. <ol style="list-style-type: none"> <li>(a) <i>Dune prograded coasts</i> Where the steep lee slope of the dune has transgressed over the beach.</li> <li>(b) <i>Dune coasts</i> Where dunes are bordered by a beach.</li> <li>(c) <i>Fossil dune coasts</i> Where consolidated dunes (eolianites) form coastal cliffs.</li> </ol> </li> <li>7. <i>Landslide coasts</i> Recognized by the bulging earth masses at the coast and the landslide topography on land.</li> </ol> <p>C. <i>Volcanic coasts</i></p> <ol style="list-style-type: none"> <li>1. <i>Lava-flow coasts</i> Recognized on charts either by land contours showing cones, by convexities of shoreline, or by conical slopes continuing from land out under the water. Slopes of 10° to 30° common above and below sea level. Found on many oceanic islands.</li> <li>2. <i>Tephra coasts</i> Where the volcanic products are fragmental. Roughly convex but much more quickly modified by wave erosion than are lava-flow coasts.</li> <li>3. <i>Volcanic collapse or explosion coasts</i> Recognized in aerial photos and on charts by the concavities in the sides of volcanoes.</li> </ol> <p>D. <i>Shaped by diastrophic movements</i></p> <ol style="list-style-type: none"> <li>1. <i>Fault coasts</i> Recognized on charts by the continuation of relatively straight steep land slopes beneath the sea. Angular breaks at top and bottom of slope. <ol style="list-style-type: none"> <li>(a) <i>Fault scarp coasts</i> For example, northeast side of San Clemente Island, California.</li> <li>(b) <i>Fault trough or rift coasts</i> For example, Gulf of California and Red Sea, both being interpreted as rifts.</li> <li>(c) <i>Overthrust</i> No examples recognized but probably exist.</li> </ol> </li> </ol>	<p>IV-2-3</p> <p>IV-2-4</p> <p>IV-3-3</p> <p>IV-2-6</p> <p>IV-2-7</p>

(Continued)

Table IV-2-1 (Concluded)	Paragraph No.
<ul style="list-style-type: none"> <li>2. <i>Fold coasts</i> Difficult to recognize on maps or charts but probably exist.</li> <li>3. Sedimentary extrusions <ul style="list-style-type: none"> <li>(a) <i>Salt domes</i> Infrequently emerge as oval-shaped islands. Example: in the Persian Gulf.</li> <li>(b) <i>Mud lumps</i> Small islands due to upthrust of mud in the vicinity of the passes of the Mississippi Delta.</li> </ul> </li> <li>E. <i>Ice coasts</i> Various types of glaciers form extensive coasts, especially in Antarctica.</li> <li>II. <i>Secondary coasts</i> Shaped primarily by marine agents or by marine organisms. May or may not have been primary coasts before being shaped by the sea. <ul style="list-style-type: none"> <li>A. <i>Wave erosion coasts</i> <ul style="list-style-type: none"> <li>1. <i>Wave-straightened cliffs</i> Bordered by a gently inclined seafloor, in contrast to the steep inclines off fault coasts. <ul style="list-style-type: none"> <li>(a) <i>Cut in homogeneous materials.</i></li> <li>(b) <i>Hogback strike coasts</i> Where hard layers of folded rocks have a strike roughly parallel to the coast so that erosion forms a straight shoreline.</li> <li>(c) <i>Fault-line coasts</i> Where an old eroded fault brings a hard layer to the surface, allowing wave erosion to remove the soft material from one side, leaving a straight coast.</li> <li>(d) <i>Elevated wave-cut bench coasts</i> Where the cliff and wave-cut bench have been somewhat elevated by recent diastrophism above the level of present-day wave erosion.</li> <li>(e) <i>Depressed wave-cut bench coasts</i> Where the wave-cut bench has been somewhat depressed by recent diastrophism so that it is largely below wave action and the wave-cut cliff plunges below sea level.</li> </ul> </li> <li>2. <i>Made irregular by wave erosion</i> Unlike ria coasts in that the embayments do not extend deeply into the land. <i>Dip coasts</i> Where alternating hard and soft layers intersect the coast at an angle; cannot always be distinguished from trellis coasts. <ul style="list-style-type: none"> <li>(a) <i>Heterogeneous formation coasts</i> Where wave erosion has cut back the weaker zones, leaving great irregularities.</li> </ul> </li> </ul> </li> <li>B. <i>Marine deposition coasts</i> Coasts prograded by waves and currents. <ul style="list-style-type: none"> <li>1. <i>Barrier coasts.</i> <ul style="list-style-type: none"> <li>(a) <i>Barrier beaches</i> Single ridges.</li> <li>(b) <i>Barrier islands</i> Multiple ridges, dunes, and overwash flats.</li> <li>(c) <i>Barrier spits</i> Connected to mainland.</li> <li>(d) <i>Bay barriers</i> Sand spits that have completely blocked bays.</li> <li>(e) <i>Overwash fans</i> Lagoonward extension of barriers due to storm surges.</li> </ul> </li> <li>2. <i>Cuspate forelands</i> Large projecting points with cusp shape. Examples include Cape Hatteras and Cape Canaveral.</li> <li>3. <i>Beach plains</i> Sand plains differing from barriers by having no lagoon inside.</li> <li>4. <i>Mud flats or salt marshes</i> Formed along deltaic or other low coasts where gradient offshore is too small to allow breaking waves.</li> </ul> </li> <li>C. <i>Coasts built by organisms</i> <ul style="list-style-type: none"> <li>1. <i>Coral reef coasts</i> Include reefs built by coral or algae. Common in tropics. Ordinarily, reefs fringing the shore and rampart beaches are found inside piled up by the waves. <ul style="list-style-type: none"> <li>(a) <i>Fringing reef coasts</i> Reefs that have built out the coast.</li> <li>(b) <i>Barrier reef coasts</i> Reefs separated from the coast by a lagoon.</li> <li>(c) <i>Atolls</i> Coral islands surrounding a lagoon.</li> <li>(d) <i>Elevated reef coasts</i> Where the reefs form steps or plateaus directly above the coast.</li> </ul> </li> <li>2. <i>Serpulid reef coasts</i> Small stretches of coast may be built out by the cementing of serpulid worm tubes onto the rocks or beaches along the shore. Also found mostly in tropics.</li> <li>3. <i>Oyster reef coasts</i> Where oyster reefs have built along the shore and the shells have been thrown up by the waves as a rampart.</li> <li>4. <i>Mangrove coasts</i> Where mangrove plants have rooted in the shallow water of bays, and sediments around their roots have been built up to sea level, thus extending the coast. Also a tropical and subtropical development.</li> <li>5. <i>Marsh grass coasts</i> In protected areas where salt marsh grass can grow out into the shallow sea and, like the mangroves, collect sediment that extends the land. Most of these coasts could also be classified as mud flats or salt marshes.</li> </ul> </li> </ul> </li></ul>	<p>IV-2-8</p> <p>IV-2-9</p> <p>IV-2-11</p> <p>IV-2-12</p>

e. *Classification schemes for specific environments.*

(1) River systems. Coleman and Wright (1971) developed a detailed classification for rivers and deltas.

(2) Great Lakes of North America. The Great Lakes have unique characteristics that set them apart from oceanic coastlines. One of the most comprehensive attempts to include these factors in a classification scheme was developed by Herdendorf (1988). It was applied to the Canadian lakes by Bowes (1989). A

simpler scheme has been used by the International Joint Commission as a basis for studies of shoreline erosion (Stewart and Pope 1992).

### IV-2-3. Drowned River Coasts - Estuaries<sup>1</sup>

*a. Introduction.* An enormous amount of technical literature is devoted to the chemistry and biology of estuaries. In recent years, much research has been devoted to estuarine pollution and the resulting damage to fish and animal habitat. For example, the famous oyster harvesting in Chesapeake Bay has been almost ruined in the last 30 years because of overfishing, urban runoff, and industrial pollution. As a result, the unique way of life of the Chesapeake oystermen, who still use sailing vessels, may be at an end. Possibly because most attention has centered on the biological and commercial aspects of estuaries, our geological understanding of them is still rudimentary (Nichols and Biggs 1985). The estuarine environment can be defined as the complex of lagoon-bay-inlet-tidal flat and marsh that make up 80 to 90 percent of the U.S. Atlantic and Gulf coasts (Emery 1967). Clearly it is vital that we gain a better understanding of their sedimentary characteristics and dynamics.

*b. Literature.* Only the briefest introduction to estuarine processes and sediments can be presented in this chapter. The purpose of this section is to introduce estuarine classification, regional setting, and geology. The reader is referred to Nichols and Biggs (1985) for an overview of the geology and chemistry of estuaries and for an extensive bibliography. Other general works include Dyer (1979), Nelson (1972), and Russell (1967). Cohesive sediment dynamics are covered in Metha (1986), and the physics of estuaries is covered in van de Kreeke (1986). Research from the 1950's and 1960's is reviewed in Lauff (1967).

*c. Classification.* Many attempts have been made to define and classify estuaries using geomorphology, hydrography, salinity, sedimentation, and ecosystem parameters (reviewed in Hume and Herdendorf (1988)). A geologically based definition, which accounts for sediment supply pathways, is used in this text.

*d. Definitions.* Estuaries are confined bodies of water that occupy the drowned valleys of rivers that are not currently building open-coast deltas. The most common definition of an estuary describes it as a body of water where "...seawater is measurably diluted with fresh water derived from land drainage" (Pritchard 1967). Therefore, estuaries would include bodies of water where salinity ranges from 0.1 ‰ (parts per thousand) to about 35 ‰ (Figure IV-2-1). However, this chemical-based definition does not adequately restrict estuaries to the setting of river mouths, and allows, for example, lagoons behind barrier islands to be included. Dalrymple, Zaitlin, and Boyd (1992) felt that the interaction between river and marine processes was an attribute essential to all true estuaries. Therefore, they proposed a new geologically based definition of estuary as:

...the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave, and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth.

These limits are schematically shown in Figure IV-2-1.

*e. Time relationships and evolution.*

(1) Estuaries, like other coastal systems, are ephemeral. River mouths undergo continuous geological evolution, of which estuaries represent one phase of a continuum (Figure IV-2-2). During a period of high

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<sup>1</sup> Material in this section has been condensed from Dalrymple, Zaitlin, and Boyd (1992).

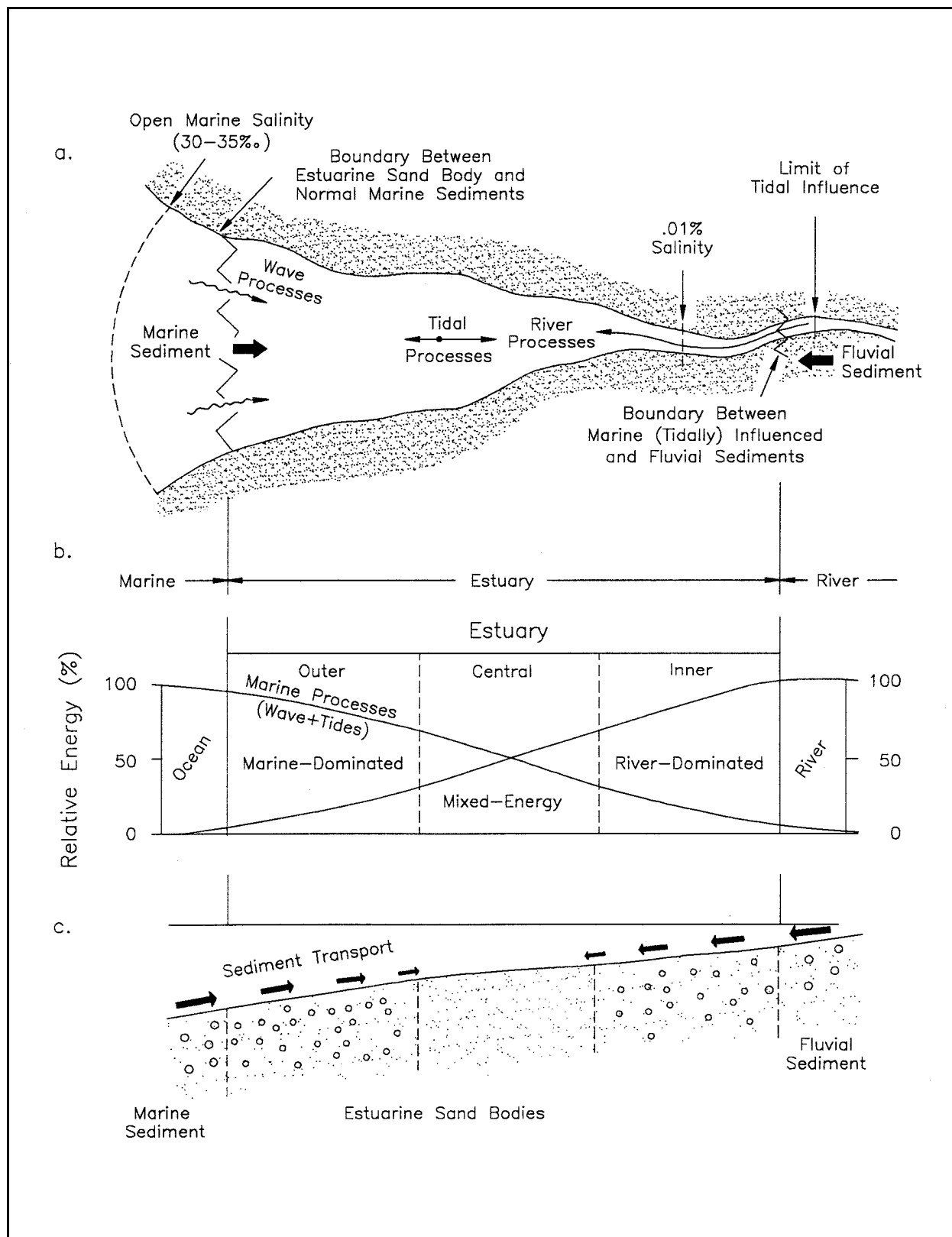
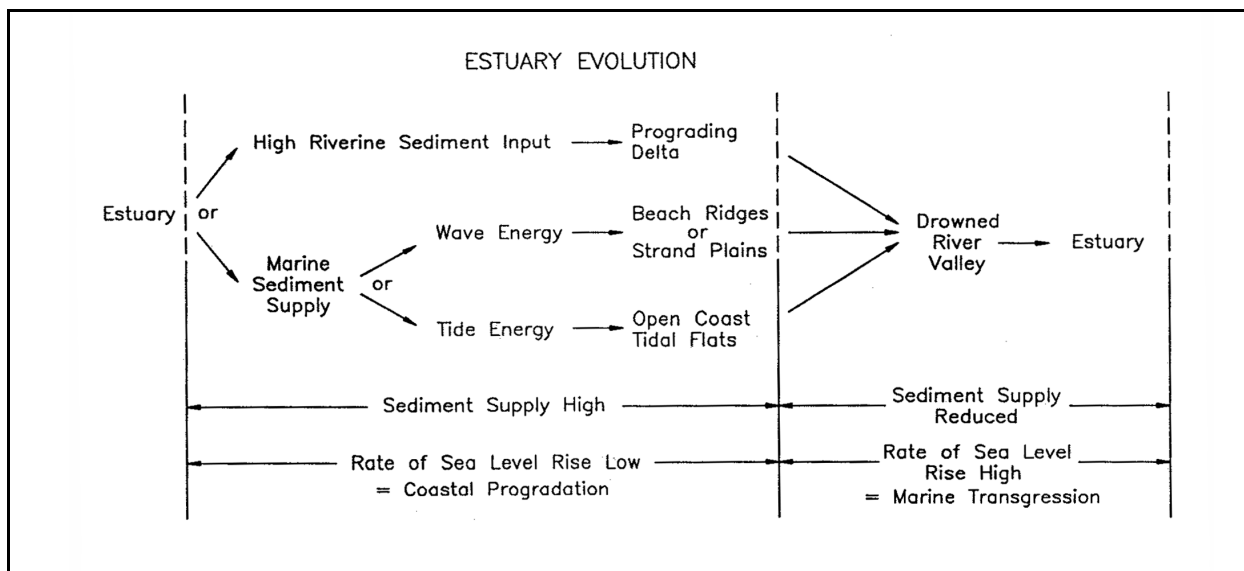


Figure IV-2-1. (a) Plan view of distribution of energy and physical processes in estuaries; (b) Schematic definition of estuary according to Dalrymple, Zaitlin, and Boyd (1992); (c) Time-averaged sediment transport paths



**Figure IV-2-2. Estuary/prograding coast evolution. Estuaries are part of a continuum of coastal landforms. With high riverine or marine sediment supply, the shore progrades (left half of figure). Later, if sediment supply is reduced, the river valley is drowned, resulting in an estuary (right half of figure)**

sediment supply and low rate of sea level rise, an estuary is gradually filled. Three coastal forms may result, depending on the balance between riverine input and marine sediment supply:

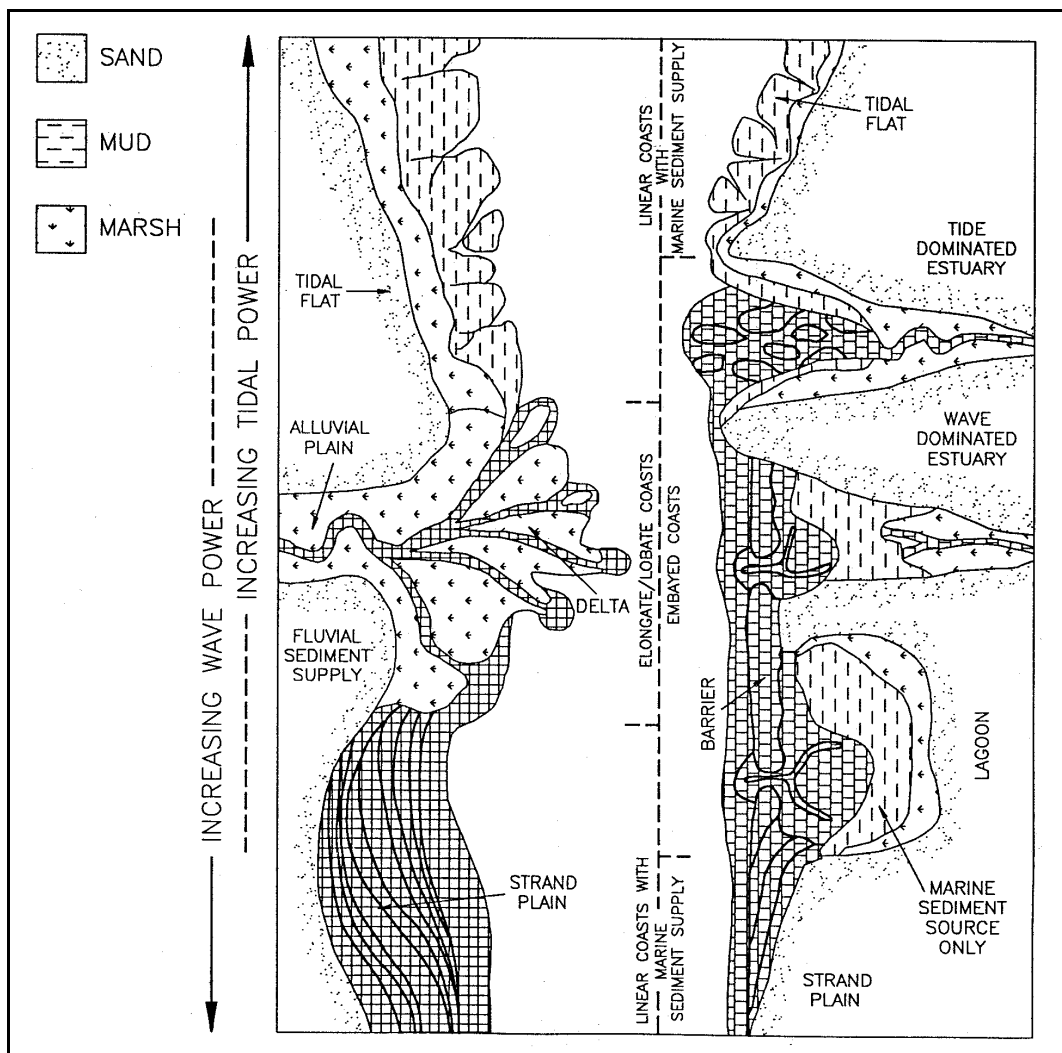
(a) If the sediment is supplied by a river, a delta is formed, which, as it grows, progrades out into the open sea (left side of Figure IV-2-3).

(b) If, instead, most sediment is delivered to the area by marine processes, a straight, prograding coast is formed. This might be in the form of beach ridges or strand plains if wave energy is dominant, or as open-coast tidal flats if tidal energy is dominant.

(c) Later, if sea level rises at a higher rate, then the river valley may be flooded, forming a new estuary (right side of Figure IV-2-3).

(2) Under some conditions, such as when sea level rise and sediment supply are in balance, distinguishing whether a river mouth should be classified as an estuary or as a developing delta may be difficult. Dalrymple, Zaitlin, and Boyd (1992) suggest that the direct transport of bed material may be the most fundamental difference between estuaries and deltas. They state that the presence of tight meanders in the channels suggests that bed-load transport is landward in the region seaward of the meanders and, as a consequence, the system is an estuary. However, if the channels are essentially straight as far as the coast, bed load is seaward throughout the system and it can be defined as a delta.

(3) Fluvial systems are controlled by their erosional base level and the sediment supply. During periods of lowered sea level, rivers incise the lower reaches of their valleys and discharge increasing amounts of sediment out onto the shelf. Deltas accumulate and fluvial channels are cut, dissecting parts of the delta plain (described in greater detail in Part IV-3-3). At the lowest stands of sea level, estuaries almost disappear and are confined to river valleys (Baeteman 1994). When sea level rises again, the valleys are flooded and the estuaries reappear.



**Figure IV-2-3. Estuary evolution, based on changes in wave or tidal power. The left half of the figure shows a prograding coast that results during times of high sediment supply. The right side shows how estuaries develop during reduced sediment supply (also refer to Figure IV-2-2). Adapted from Boyd, Dalrymple, and Zaitlin (1992)**

*f. Overall geomorphic characteristics.* The geologic definition of estuary implies that sediment supply does not keep pace with the local sea level rise; as a result, estuaries become sinks for terrestrial and marine sediment. Sedimentation is the result of the interaction of wave, tide, and riverine forces. All estuaries, regardless of whether they are wave- or tide-dominated, can be divided into three zones (Figure IV-2-1):

- (1) The *outer zone* is dominated by marine processes (wave and tidal currents). Because of currents, coarse sediment tends to move up into the mouth of the estuary.
- (2) The *central zone* is characterized by relatively low energy, where wave and tidal currents are balanced over the long term by river currents. The central zone is an area of net convergence of sediment and usually contains the finest-grained bed load present in the estuary.
- (3) The *inner zone* is river-dominated and extends upriver to the limit of tidal influence. The long-term (averaged over years) bed load transport in this region is seaward.

*g. Energy factors and sedimentary structures.*

(1) Wave-dominated estuaries.

(a) This type of estuary is characterized by high wave energy compared to tidal influence. Waves cause sediment to move alongshore and onshore into the mouth of the estuary, forming sandbars or subaerial barriers and spits (Figure IV-2-4a). The barrier prevents most of the wave energy from entering the central basin. In areas of low tide range and small tidal prism, tidal currents may not be able to maintain the inlet, and storm breaches tend to close during fair weather, forming enclosed coastal ponds. Sediment type is well-distributed into three zones, based on the variation of total energy: coarse sediment near the mouth, fine in the central basin, and coarse at the estuary head. A marine sand body forms in the high wave energy zone at the mouth. This unit is composed of barrier and inlet facies, and, if there is moderate tide energy, sand deposited in flood-tide deltas (Hayes 1980).

(b) At the head of the estuary, the river deposits sand and gravel, forming a bay-head delta. If there is an open-water lagoon in the central basin, silts and fine-grained organic muds accumulate at the toe of the bay-head delta. This results in the formation of a prodelta similar to the ones found at the base of open-coast deltas (deltaic terms and structures are discussed in Part IV-3). Estuaries that are shallow or have nearly filled may not have an open lagoon. Instead, they may be covered by extensive salt marshes crossed by tidal channels.

(2) Tide-dominated estuaries.

(a) Tide current energy is greater than wave energy at the mouth of tide-dominated estuaries, resulting in the development of elongate sandbars (Figure IV-2-4b). The bars dissipate wave energy, helping protect the inner portions of the estuary. However, in funnel-shaped estuaries, the incoming flood tide is progressively compressed into a decreasing cross-sectional area as it moves up the bay. As a result, the velocity of the tide increases until the effects of the amplification caused by convergence are balanced by frictional dissipation. The velocity-amplification behavior is known as *hypersynchronos* (Nichols and Biggs 1985). Because of friction, the tidal energy decreases beyond a certain distance in the estuary, eventually becoming zero.

(b) As in wave-dominated estuaries, riverine energy also decreases downriver from the river mouth. The zone where tide and river energy are equal is sometimes called a balance point and is the location of minimum total energy. Because the total-energy minimum is typically not as low as the minimum found in wave-dominated estuaries, tide-dominated estuaries do not display as clear a zonation of sediment facies. Sands are found along the tidal channels, while muddy sediments accumulate in the tidal flats and marshes along the sides of the estuary (Figure IV-2-4b). In the central, low-energy zone, the main tidal-fluvial channel consistently displays a sinuous, meandering shape. Here, the channel develops alternate bars at the banks and, sometimes, in mid-channel.

(c) A bay-head delta is usually not present in the river-dominated portion of tidally dominated estuaries. Instead, the river channel merges directly into a single or a series of tidal channels that eventually reach the sea.

(3) Estuarine variability.

(a) Wave-to-tide transition. As tide energy increases relative to wave energy, the barrier system at the mouth of the estuary becomes progressively more dissected by tidal inlets, and elongate sandbars form along

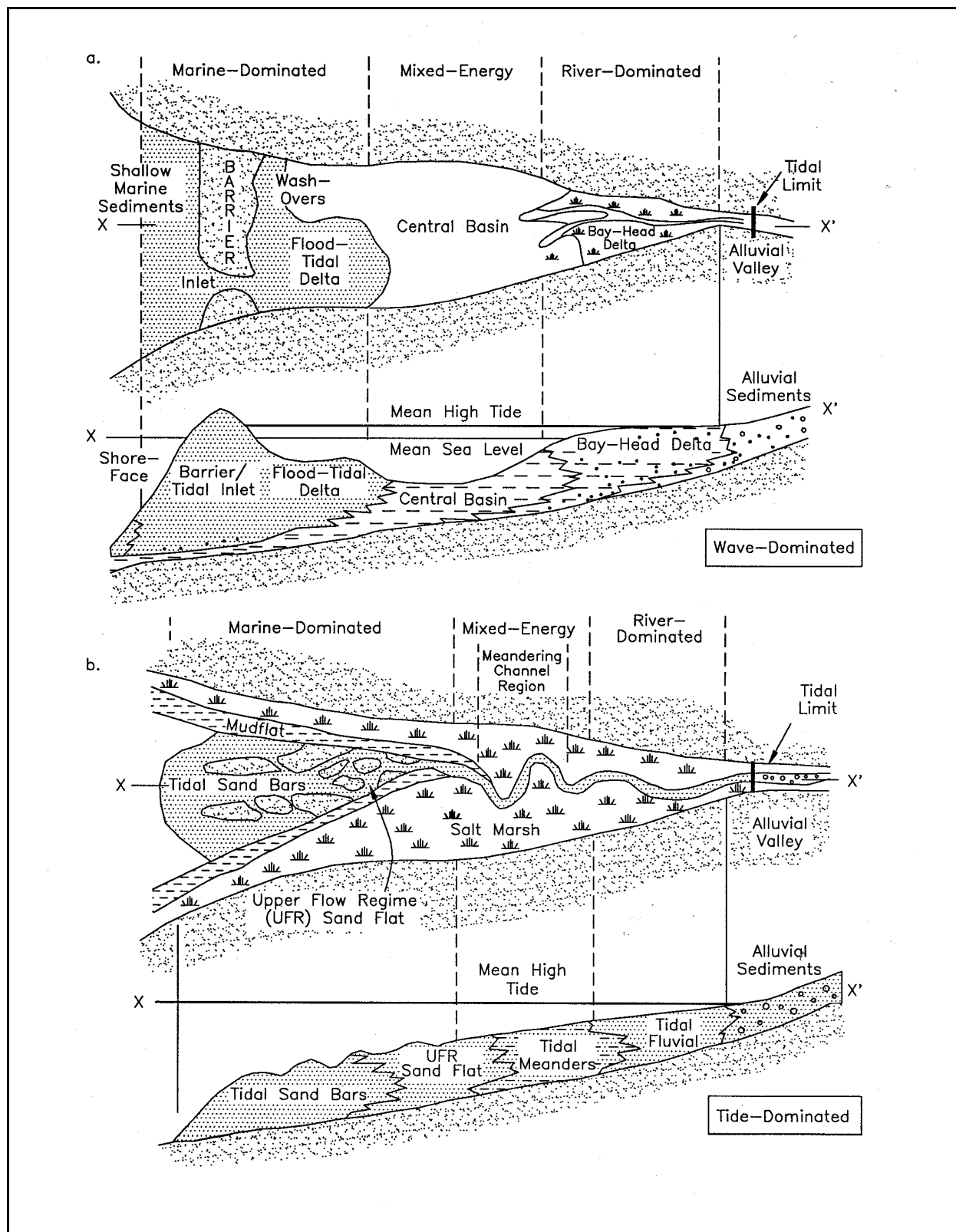


Figure IV-2-4. Morphologic models of (a) wave-dominated and (b) tide-dominated estuaries (adapted from Dalrymple, Zaitlin, and Boyd (1992)). Wave-dominated estuaries are common along the mid-Atlantic coast of the United States. Tide-dominated estuaries are found in Maine, Massachusetts, and the mid-Atlantic Bight

the margins of the tidal channels. As energy levels increase in the central, mixed-energy part of the estuary, marine sand is transported further up into the estuary, and the muddy central basin is replaced by sandy tidal channels flanked by marshes.

(b) Effects of tide range. The inner end of an estuary has been defined as the limit of detectable tidal influence. Therefore, the gradient of the coastal zone and the tide range have a great influence on the length of estuaries (Dalrymple, Zaitlin, and Boyd 1992). Estuaries become longer as gradient decreases and tide range increases.

(c) Influence of valley shape. The shape of the flooded valley and the pre-existing geology also control the size of the estuary and the nature of sediment deposition. This is particularly evident during the early phases of estuary infilling, before erosion and deposition have modified the inherited geology. For example, tidal-wave amplification is less likely to occur in irregular valleys (Nichols and Biggs 1985). The resulting estuaries are more likely to become wave-dominated. Chesapeake Bay, with its extensive system of tributary valleys, is an example of this type. In contrast, estuaries that initially or later have developed a funnel shape are more likely to be tide-dominated and hypersynchronous (for example, the Gironde Estuary of France.)

(d) Geologic setting. Coastal plain gradient, part of the overall plate tectonic setting, is one factor that determines estuary volume. Sea level rise over a flat coastal plain on a passive margin like the Gulf of Mexico creates long estuaries with large volume. An equivalent rise on a steep, active-margin coast like the U.S. Pacific coast will result in a much smaller estuary volume (Boyd, Dalrymple, and Zaitlin 1992).

#### *h. Estuarine sediments.*

(1) Because estuaries occupy drowned river valleys, they function as sinks for enormous volumes of sediment. Estuarine sediments are derived from various sources including rivers, the continental shelf, local erosion, and biological activity. Sedimentation is controlled by tides, river flow, waves, and meteorology. The lower-energy conditions of estuaries, as opposed to those found on open coasts, allow for the deposition of fine-grained silts, muds, clays, and biogenic materials. Estuarine sediments are typically soft and tend to be deposited on smooth surfaces that limit turbulence of the moving water. When allowed to accumulate, these materials consolidate and undergo various chemical and organic changes, eventually forming cohesive sediments.

(2) The shores of estuaries and certain open-water coasts in low-energy environments (e.g., coastal Louisiana, Surinam, Bangladesh, and Indonesia) are characterized as having smooth, low-sloping profiles with turbid water occurring along the shore and extending well offshore (Suhayda 1984). These areas usually exhibit low and vegetated backshores and mud flats that are exposed at low tide. These conditions are also found in Chesapeake and Delaware Bays.

(3) Nichols and Biggs (1985) describe the movement of estuarine sediments as consisting of four processes:

- (a) Erosion of bed material.
- (b) Transportation.
- (c) Deposition on the bed.
- (d) Consolidation of deposited sediment.

These processes strongly depend on estuarine flow dynamics and sediment particle properties. The properties most important for cohesive sediments are interparticle bonding and chemical behavior because these parameters make cohesive sediment respond quite differently to hydrodynamic forces than do noncohesive sediments. Due to the cohesive bonding, consolidated materials (clays and silts) require higher forces to mobilize, making them more resistant to erosion. However, once cohesive sediment is eroded, fine-grained clays and silts can be transported at much lower velocity than is required for the initiation of erosion.

#### IV-2-4. Drowned Glacial Erosion Coasts

*a. Introduction.* During the Pleistocene epoch, massive continental glaciers, similar to the present Antarctic and Greenland ice caps, covered broad parts of the continents. The glaciers waxed and waned in cycles, probably because of climatic variations, causing vast changes to the morphology of coastal regions in the northern latitudes. As a result, glacially modified features dominate the northern coasts and continental shelves, although in many areas marine processes have reworked the shore and substantially modified the glacial imprint.

*b. Erosion and sediment production.* Because glacial ice is studded with rock fragments plucked from the underlying rock, a moving glacier performs like a giant rasp that scours the underlying land surfaces. This process, driven by the great size and weight of the ice sheets, caused enormous erosion and modification to thousands of square kilometers during the Pleistocene epoch.

(1) Fjords. The most spectacular erosion forms are drowned glacial valleys known, as *fjords*, that indent the coasts of Alaska, Norway, Chile, Siberia, Greenland, and Canada (Figure IV-2-5). The over-deepened valleys were invaded by the sea as sea level rose during the Holocene epoch. Today, fjords retain the typical U-shaped profile that is also seen in formerly glaciated mountain valleys. Fjords and other drowned glacial erosion features give Maine a spectacular, rugged coastline (Figure IV-2-6).

(2) Depositional features. As a glacier moves, huge amounts of sediment are incorporated into the moving mass. When the ice melts at the glacial front's furthest advance, the sediment load is dropped. Although the major part of the transported material is dumped in the form of a terminal moraine, some sediments are carried further downstream by meltwater streams (Reineck and Singh 1980). The result is a number of distinctive geomorphic features such as drumlins, fjords, moraines, and outwash plains that may appear along the coast or on the submerged continental shelf (Figure IV-2-7). During submergence by the transgressing sea, the features may be modified to such a degree that their glacial origin is lost. This is especially true of outwash, which is easily reworked by marine processes. The original town of Boston was settled on drumlins in the 1600's (Figure IV-1-18), and the islands in Boston Harbor are reworked drumlins (Figure IV-2-8). Nantucket Island, Block Island, and Long Island are partially submerged moraines that have been extensively reworked (Figure IV-2-9).

*c. Variability.* Glaciated coasts typically display a greater variety of geomorphic forms than are seen in warmer latitudes. The forms include purely glacial, glacio-fluvial, and marine types (Fitzgerald and Rosen 1987). Complexity is added by marine reworking, which can produce barriers, shoals, gravel shores, and steep-cliffed shores. Because of the steep slopes of many glacial coasts, slumping and turbidity flow are major erosive agents. In northern latitudes, the shallow seafloor is gouged by icebergs. In summary, classification of shores in drowned glacial environments can be a major challenge because of the complicated geological history and the large diversity of structures.

*d. Atlantic coast.* A fundamental division of coastal characteristics occurs along the Atlantic coast of North America due to the presence of glacial moraines. The Wisconsin terminal moraine formed a prominent series of islands (i.e., Long Island, Block Island, Nantucket, and Martha's Vineyard) and offshore banks